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Abstract – Knowledge management is one of the critical issues for the improvement of enterprise performances. Different methods exist for extracting and formalizing knowledge in order to create knowledge-based applications. Most of integrated design and manufacturing technological processes are more or less based on knowledge that has been translated into models and then into Knowledge-Based Computer-Aided Applications. This paper presents some examples of bases and applications concerning the issues of knowledge-based engineering for integrated design and manufacturing

Keywords: Integrated design and Manufacturing, Knowledge-based engineering, Knowledge value, Virtual Engineering.

1 Introduction

Recent evolutions have transformed the key issues of enterprises performance. Knowledge-based digital (virtual) engineering increasingly constitutes a strategic purpose, in particular for mechanical engineering companies. The actual strategic need is the definition of an integrated design and manufacturing environment, built from knowledge-based applications, that constitutes an efficient PLM system. This strategic need mainly comes from the new relationship that subcontractors have with their OEMs in an extended or virtual enterprise context. So, this is both useful and necessary that small and medium-size enterprises (SME) in the field of mechanical engineering integrate new methods and tools for PLM integration. SMEs need specific PLM environments but the main difficulty is to succeed in defining the real needs and to formalize the knowledge required for a global efficiency. The required approach should provide assistance for costing, development and industrialization of products, manufacturing evaluation and the same issues related to the complete life-cycle of the product. It is based on the capitalization, reuse and extension of experts' knowledge. In order to have a realistic definition of the requirements of such system, one efficient way is "to go inside" the SMEs to extract the main needs in terms of collaborative work, technical processes, technical data management and more generally for PLM needs definition. Based on representative case-studies that constitute the panel to start the definition and the formalization of the needs, a generic solution is built at the conceptual level. But such proposition is possible because of a jointly characterization of a generic enterprise object model and also of a generic method for expertise extraction and formalization. Such expertise is modeled and the models are used for the specification and the development of a knowledge-based PLM environment that fits the requirements of each expert. In this paper we present and illustrate a global approach based on a generic model for enterprise objects and processes, also based on a generic extended approach for expertise formalization and finally on the use of these model and method for an inductive process based on three immersive case studies, and, finally, some first synthesis for the specification of a generic PLM system dedicated to a framework of mechanical engineering field organized as an extended enterprise..

2 A generic model for Enterprise objects

The first need is to propose a model dedicated to the representation of any enterprise object. One of the main goals is to fit the requirement of being able to model and manage the whole information of the whole product lifecycle. To achieve this goal, the FBS-PPRE model is proposed and defined in brief hereafter.
In [1], a brief comparison between the views included in the different methodologies known in the literature is proposed. This shows that there is a lack of completeness in all these approaches. For example, the external effects are not modeled and often not taken into account.
These approaches do not tend to be universal. Nevertheless, they are of great interest in their respective application area. Their use can also be complementary. The worst thing is that the integration of these approaches remains quite uneasy, with a consequence that making a view of the whole enterprise is quite difficult.
Another observation is that the dynamic of the views remains partial, restricted to the product view: in most of these models, the resources or the processes structures being not able to evolve.

2.1 Different views of an Enterprise object

It is assumed [1] that "Enterprise object" is a generic concept dedicated to encapsulate the PPRE concepts: Process, Product, Resource and External effect (even if this last concept is also dependant of the context in relation with the enterprise). The PPRE concepts represent in fact the four roles that a given enterprise object can play during its lifecycle. Based on this assumption, this means that each enterprise object could be described with the same model. The "Enterprise Object" generic concept is thus used and defined as "an entity playing a role in the company". As a given object can play different roles successively, this concept aims at managing the different objects independently of their roles [2].
The process concept is a sequential, spatial and hierarchical organization of activities using resources to make products or services (also generally called outputs).
The product concept is the result of the process, the object that the process intends to modify, to which the process is supposed to add value.
The resource concept is an object contributing to the process without being its purpose. It could be a consumable resource.
The external concept is an object acting as a constraint (positive or negative, even neutral) on the process / product / resource system. It is a part of the context that can disturb the process progress.
It is also assumed [1] that each enterprise object can be characterized by three views: functional, behavioral and structural views which are the basic concepts of the FBS (Function-Behavior-Structure) approach [2] [3] [4] [5].
In the functional view, the functions describe the aim of an object. The operational functions are formulated independently of any particular solution.

On the opposite, the technical functions depend on the technical choices.
In the behavioral view, the behavior describes the dynamic aspect of an object. It includes a set of rules (continuous models) and sequential states graph (discrete model) representing the transformation of an object stimulated during a process.
In the structural view, the structure defines the elements that are parts of the object. It defines also the attributes of these parts.

2.2 Natures of an Enterprise object

The Enterprise objects cannot be classified by their roles (they change during their lifecycle and, consequently, they are circumstantial). At the opposite, the Enterprise objects can be classified by their nature.
It has been assumed that, in coherency with the systemic approach, five object natures can be used:
- Material (object that can have a concrete form);
- Organizational;
- Temporal (object that can play a process role);
- Software (including information, decisions, the generated documents);
- Energy.

"Object nature" is a concept linked to intrinsic parameters of the object.

2.3 Behaviour of an Enterprise object

The behavior management is an originality of the FBS-PPRE model. It is constituted on one hand of "processes" and on the other hand of a description that will be the same for the products, the resources and the external effects.
The process concept (in the center of the representation) plays a major role in the FBS-PPRE model:
- It links the different objects playing a role in the activity. It helps at defining the context;
- It also helps at managing the behavior of the product, of the resources and of the external effects.

The states are representative of the structure changes. They are the inputs and outputs of the process element. They represent the discontinuous behavior of the objects.

2.4 Use and prospective issues about the FBS-PPRE model

Knowledge formalization for PLM is one of the main industrial challenges. It highlights the role of knowledge capitalization and management. But, the development of the knowledge-based applications of of knowledge bases content implies a real integration: of all the view points of Enterprise objects, depending on the different ontologies they refer to. So, on a general point of view, the main difficulty remains the representation of the knowledge in order to insure its interpretation, its sharing and its keeping.
The FBS-PPRE model allows advances principally in three domains: the completeness of the modeling, the management of the dynamic of the objects, the conceptual unification.
As regards completeness, the model offers a wider view than the usual approaches. Each object having an influence on the enterprise processes (defined as a temporal, spatial and hierarchical organization of activities) is taken into account through its role of product (the product is the result of the process), of resource (the resource is contributing to the process without being its purpose) or of external effect (the external effect is then acting as a constraint - positive or not - on the process). Furthermore, each object is modeled with the same views: the functional, the behavioral and the structural views.
Due to its definition, the behavioral view of an object is always linked to a process. But, different behaviors can be taken into account: the model makes it possible to characterize the behavior of an object during its use process (the object has then a role of resource), but it also makes it possible to keep the evolution of an object during a process of design, of realization, of dismantling, of recycling, etc (the object has then a role of product). Moreover, this modeling of the dynamic applies whatever the nature of the object: it also makes it possible to manage natively the transformation of the temporal objects.
This strongly increased completeness, in particular with the management of the dynamic of all the objects, Due to the generic views of the FBS-PPRE modeling, the enterprise objects can be described according to the same formalism independently of their circumstantial roles of process, of product, of resource, or of external effect.
Furthermore, the FBS-PPRE model constitutes a real conceptual unification independently of the nature of the Enterprise objects (temporal, material, software, organizational or energy). The model is thus very compact and easier to apprehend: its implementation and its maintenance are easy.
These conceptual elements thus constitute an essential support for the representation of knowledge.
The adoption and the deployment of the FBS-PPRE model contribute to the analysis, the specification and the follow-up of the enterprise processes. They can lie with an ISO 9001 quality certification process: the objectives of this standard are indeed in perfect adequacy with FBS-PPRE.
To use this model in the company, a reliable and effective information system should be configured and implemented. This has already been successful

in several particular enterprises, mainly in the context of our research collaborations.
This contribution is the base of our investigation about knowledge formalization. Anyone can speak about knowledge-based application but the core representation of knowledge needs a structured modeling that enables to support knowledge encapsulation and the model transformation phases that are required for the definition of the knowledge-based applications.
So, based on this generic and unified Enterprise model and on its ability to formalize knowledge content, it has been proposed a methodological contribution. It consists in the proposition of an extended knowledge extraction and formalization method that can be used for the definition of knowledge-based applications for technical expertise mainly used during the design phases, in order to be able to evaluate the performances of the product (manufacturability, maintainability, etc…).

3 Proposition of a generic method for knowledge capitalization

This proposition is mainly based on the MOKA (Methodology and tools Oriented to Knowledge based engineering Applications) [6] [7] approach and its ontology that has been extended in order to be able to fit the technological expertise formalization [8]. This was necessary because of the need to develop industrial knowledge-based engineering applications. The context of the experiments is a French national project (USIQUICK : www.usiquick.com) dedicated to 5-axis machining of complex aeronautic parts.

3.1 USIQUICK: a KBE application for 5-axis machining of complex parts

The project was started with the aim of developing a knowledge-based engineering system to help experts to define the process planning related to complex mechanical parts that need to use 5-axis machining.
The project involved eight partners: An aircraft manufacturer, who proposed expertise about process planning for complex parts, a CAD/CAM leader for the industrialization of the software solution, five laboratories ensuring the scientific coherence of the project and proposing innovative solutions to solve strategic locks and a French-government institute (Cetim) who analyzed the possible use of the project results in other fields and proposed extra test cases and tool databases.
Globally, the project focuses on the definition of milling process plans mainly in complex aeronautic part manufacturing with a high amount of re-engineering and this implies particular geometries and processes.

In order to optimize the information flow from design to production, a three-step method is proposed [9]: 1) Transformation phase which consists in an analysis of the part to compute a maximum of information registered in an appropriate level of feature and to compute the machinability of faces, 2) Preparation phase where the synthesis templates of the previous phase are presented to the user and, with appropriate tools, the process plan skeleton can be built and constrained, 3) Automation phase where the unconstrained choices are automatically optimized and a complete documentation is proposed by the system. These phases became the three major modules of the developed engineering tool based on the formalization and the integration of expert knowledge.
One of the project's challenges was to translate knowledge that has been expressed in form of legacy specifications for the development of the system into a computerized form so that the computer can use it. The difficulty is thus to select the right methods and tools for supporting and structuring such transfer. One solution could be to structure the knowledge within a knowledge base (KB). The building of this KB implies the deployment of a capitalization process to help and guide the knowledge treatments. Capitalizing knowledge consists in processing and treating knowledge to prepare it for management activities. This capitalization will enable knowledge to be shared through a specific form making it understandable by each actor of the project.
Knowledge capitalization is the process of capturing and formalizing expertise before its implementation in a system. The aim of knowledge capitalization is to develop methods and tools that make the task of capturing and validating expert knowledge as efficient and effective as possible. Experts tend to be important and busy people; hence it is vital that the methods used minimize the time each expert spends off the job taking part in knowledge acquisition sessions [10].
To reach the multi-experts collaboration, the knowledge sharing and reuse within the USIQUICK context, we propose to capitalize the knowledge in two major phases: a capture phase and a formalization phase.

3.2 Capitalization process proposal

According to the KBE systems development principle, knowledge must be identified, captured, analyzed, structured and formalized in a way that it could be accessible and reusable by each one. However, this principle does not allow any distinction between the activities handling the knowledge content (this means knowledge itself) and those handling its form.

What we are proposing is not completely different or contradictory with KBE development principle. Our aim is to structure all these activities according to the knowledge aspect addressed at each stage of the capitalization process. This structuring consists in separating the activities that handle the knowledge itself from those handling its form. This distinction tends to help knowledge engineers during capitalization activities deployment.

This structuring can also be considered as working on the knowledge's state. Indeed, working on the knowledge content consists in transforming its state from a raw state (independently of being explicit or tacit) to a structured one. And working on the form, deals with the representation of the knowledge to go from a structured state to a formalized state. The transition between the two states is based on the design of a knowledge base. This base constitutes a knowledge repository that can be accessible and which will be the knowledge reference

So, the first step is Knowledge capture. This is the process that transforms the human experts' knowledge into formulated knowledge that can be used directly by an expert system or by a computer system. This process can be refined in three major steps: the elicitation step, the analysis step and the structuring step.

Several elicitation techniques exist depending on knowledge source's type. Within the USIQUICK project, the elicitation had to be done from documents that represent legacy specifications for the development of the final system. Consequently, among the existing methodologies for KBS and KBE development, the only one that can meet our needs is MOKA. This is because it offers the possibilities of eliciting knowledge from documents within engineering domains through its ontology. An ontology is a set of different interrelated concepts that describe a given domain [11]. MOKA describes in terms of rules, processes, modeling techniques and definitions the necessary stages for the specification of KBE systems. MOKA provides a framework both for capturing and for representing knowledge. This framework works at two levels: informal level and formal level. The first one is relatively simple and oriented to represent and formalize knowledge in language that can be understood by experts without being specialist in formalization languages. The advantage of this level is that it makes the validation of the acquired knowledge possible. This level makes also the communication between the expert, the knowledge engineer and the software developer easier. The second level is more formal and aims to represent and store knowledge in an encoding form in order to plug it into computers.

The MOKA spirit is not different from the approaches proposed within the other knowledge management methodologies, the difference lies in the deployment strategy. The other point that differentiates it from the other methods is about the concepts it proposes to analyze related to the application domain. MOKA proposes the ICARE ontology based on five generic knowledge object types (Illustrations, Constraints, Activities, Rules, Entities) and relations among them to describe the domain. These objects are also defined as well as their use constraints. Starting from this ontology, our first step was the identification of the knowledge objects. The identification step is a preliminary domain investigation and analysis that aims to recognize the knowledge elements or objects that must be acquired. The specifications we got consist of texts, tables and images in MS Word format. The domain library, which approximates domain ontology, consists of technical sentences condensed from legacy specifications.

The use of the MOKA ontology allowed us to identify a great number of knowledge objects. However, there is some knowledge related to, for example, resources or functions, that have been missed. Facing this insufficiency, the concept of resource (R) has been introduced to encapsulate knowledge about the different tools and machines used by manufacturing processes (or operations) to realize geometries. The concept of function (F) was also introduced to identify what is the objective of the reasoning activities. According to these two new concepts, the ICARREF ontology has been proposed in order to better fit the manufacturing domain requirements [8].

At this stage the knowledge to be kept has been identified and the elicitation can be done completely by an extraction strategy. The extraction consists of recognizing a subset of knowledge objects and their relationships, and then associating them with applicable fragments of the specifications. The eventual output of extraction can be in plain text, in XML, or in Excel form, depending on the application of the supported software. Once the knowledge extracted it must be analyzed. This analysis has two objectives: its analysis and its structuring.

The structuring step is achieved using trees and diagrams according to the MOKA approach. Knowledge objects having the same type are linked using trees with "Is a" and/or "Is composed of" relation types. Knowledge objects having different types are linked using diagrams. For diagrams building the relations are defined according to the objects they link. It can be "Has a rule", "Has a constraint", "Has a function", etc.

At this stage, the three steps of the capture phase have been done and a first representation of the knowledge is built. This representation will enable the evaluation of the knowledge.

The evaluation consists in analyzing the knowledge according to two criteria: completeness and feasibility.

The completeness indicates if, as transmitted by the expert in the specifications, this knowledge is enough to define the process planning for specified geometries. It allows also identifying if for specified utilization of the application, context for each knowledge object is well described. This criterion highlights the additional knowledge to capture or to explain more that it has already been done. Each one knows that there is a gap between the "real world" and the "computer's world". The analysis of the feasibility aims to point out the knowledge that cannot be coded as specified by the expert and that requires to develop additional algorithms to make its automation possible.

The USIQUICK experience has shown that considering the two knowledge aspects separately, the content and the form, helps to decrease the complexity of knowledge based engineering system development. In summary, the capitalization process we propose aims to structure knowledge engineering activities deployment (Figure 1).

It has to be highlighted that the generic concepts of the FBS-PPRE model constitute the foundations of the new extended ICARREF ontology. The generic concepts have been adapted to the need of elicitation and representation of knowledge.

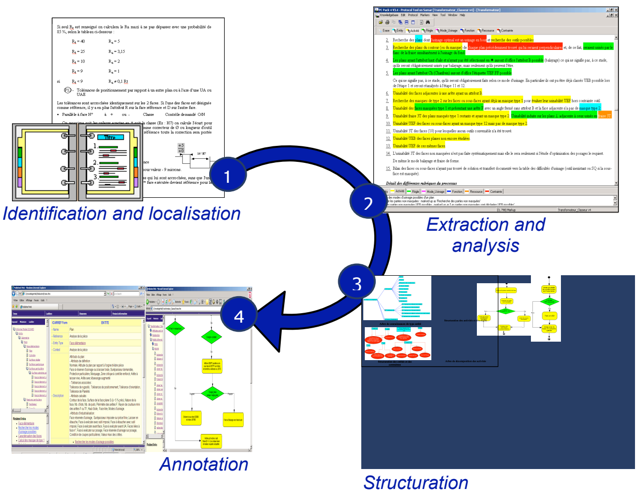

Figure 1. Synthetic view of the global process

Based on such a model, a process and a method, we actually focus on the generalization of our approach for a generic definition of PLM systems for SMEs. The content of our actual results and perspectives in such a way are described in the following sections.

4 Specification of a generic PLM system for SME's extended enterprise

Mechanical engineering industries are faced with growing challenges. After having refocused on their core business in order to increase efficiency, they are now encouraged to acquire more diversified skills. Market globalization and an increase of customer demand have forced companies to produce more complex and customized products in a shorter lead time. To solve this paradox (refocus on the core business and need of multiple specific skills), companies have setup networks in order to pool and share their mutual skills. These networks are built for a specific project which is called 'virtual enterprise', or 'extended enterprise' when it is done over a longer period.

One of the key points of the success of such a structure is the ability to communicate on the target product. Products that generate a large amount of information, the classical communication system (phone/fax/email used by 90% of companies) is not structured enough to enable efficient cooperation. For many years, software has been developed to pool all this information. From the EDM (Electronic Document Management) in the 80's to the PDM (Product Data Management) and the PLM (Product Life cycle Management) nowadays, the companies and particularly the contractors understand the benefit of such approaches and software.

Within this context Cetim (an industrial technical centre that represents 7800 French mechanical industry companies) has performed a survey on digital and collaborative engineering for the mechanical engineering companies [12]. This survey showed that only 5% of SMEs of fewer than 100 people use a PLM system to manage their technical data. However, more than 70% of these same SMEs consider as important the reuse of knowledge, the share of information within the company and outside, the security of information access and storage and the follow-up of modifications [13]. And these are the exact functionalities offered by the PLM software tools.

After many visits to SMEs, the contractors see the main obstacles to a PLM deployment as being not only the cost but also the complex nature of the setting, use, and maintenance. It seems, however, that the SMEs in the mechanical engineering industry have very specific needs in terms of PLM. 70% of these companies have customers in various business fields (mainly in the automobile and aeronautic sectors). As a consequence, they have a lot of technical skills to manage at the same time because the contractors use different CAD and PLM systems. There is a true need for PLM in SMEs in the mechanical industry, but there are some obstacles that stand in the way of this development.

4.1 – PLM: from concept to meta-modeling

An acceptable definition of PLM is: "A strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination and use of product definition information across the extended enterprise from concept to end of life - integrating people, processes, business systems, and information" [14].

Much work has been done in this field, especially in the aeronautic and automobile sectors in order to propose technical data management methods [15] [16]. Some others try to address the SME specificities and propose solutions such as Delplace for sand casting foundries [17].

PLM relies on a data model being composed of business objects that intervene in the business processes. Several modelling methods and languages have been developed so as to model these objects. Many modeling languages enable these objects and related activities to be represented such as SADT, IDEF3, BPMN [18] or FBS-PPRE.

Nevertheless, in an extended enterprise context, it is necessary to be able to communicate together. Therefore standardized models are required to enable sharing or communication between companies that have not made the same choice of modeling.

Much work has been done in different sectors to increase the interoperability of data models with the standards, using mainly the STEP standard (STandards for the Exchange of Product model data) [19] [20].

Hence the creation of PDM Schema [21] tried to unify the different information models of STEP APs using their common objects.

It seems that if many methods exist for modeling business objects, their use for the creation and maintenance of a data model that supports PLM is not detailed enough for industrial exploitation. We will keep the FBS-PPRE modeling method [1] which enables the dynamic representation of enterprise objects Moreover we can notice that in spite of the existence of standards, it is still difficult to get a data model both adapted to the company and interoperable with the standards.

4.2 – Research approach

Our approach aims to propose a methodology in order to structure and manage the technical data of companies in the mechanical industry in an extended enterprise context. To define this methodology and to build a common data model for the different companies, we have implemented an inductive research/action practice, based on a spiral cycle approach, typically consistent in terms of scientific experimentation:

The first phase has been to interview companies to extract the present practices in terms of digital and collaborative engineering, and the best practices to implement. Benchmarking has also been done on existing software tools to list the functionalities and their ability to meet SME needs.

Then we created a typology [22] [23] to choose pilot companies representative of the mechanical industry. We selected different companies to cover the whole mechanical industry.

Finally we went into the different companies so as to directly and inductively integrate the technical data structuring and managing methods. This phase is coupled with the implementation of the methods with real data in the companies to verify the gap between our proposal and the objectives. From the initial situation of each of the companies, we act by inductive research/action to arrive at the final state that we defined during the audit phase.

During this phase, we have formalized a general method of managing technical data, and created a meta-model. This approach is compatible with standards and may be used in an extended enterprise context.

4.3 – Immersion in companies

The first immersion enabled us to put into practice methods of technical data structuring and management, adapted to the chosen companies. In order to do this, we analyzed the needs of the company in terms of PLM..

The PSL CONCEPT company produces and sells equipment for ships. Among these products, there are reserve rudders, pulleys and tackles, sheaves, jam cleats and various accessories.

This company organizes the main part of its products into families. The main needs of this company are as follows: Knowledge capitalization, BoM management, Reference management, Quotation, Archive management.

We applied the axiomatic design principle [24] [25] [26] to link the functional parameters to the design parameters in order to decline it into the technical data structuring and management of a product family [23]. We broke down the different functions of the family, and then we created a set of functional dimensioning parameters for the products in order to link those parameters to the different functions. In summary, we propose a global approach to meet the specific PLM needs of this company [22] [27]. The implementation of the software based on this approach and the results that we have obtained (the design time for a new pulley has gone from hours to minutes) prove that the proposed approach corresponds to the needs of this kind of company (type II), in the mechanical industry.

The second pilot company is named CAPRICORN. This company manufactures crankshafts, connecting rods and pistons for the up market automotive industry and racing cars. It is a type III company in our typology: "elementary parts manufacturer".

This kind of company has problematic manufacturing technical data. The elementary parts manufacturers directly receive their drawings and CAD models from their customers. Then they add their expertise to draw up the plan of procedure of the product and produce it.

The audit phase makes us focus on the following initial problems: External exchange, Knowledge capitalization, Documentation, Internal exchange: Once the documentation made it has to be sent to the manufacturing department. If a modification occurs, the right version must be sent to this department.

To respond to those needs, we chose to structure the technical data in three groups. The information from the product, directly extracted from the STEP file, the information from the work centers and the craft rules, both collected during the audit phase. This case study enables us to identify the different technical data used by the planning department during the industrialization phase. It also enables us to extract the knowledge to use those data internally as well as externally via the exchange with the customer and the production department.

The third case study is SMP, a grinding machine producer. This company is a type I, “machine producer”. Due to the high number of components of its products and its high customization, this type of company often encounters bill of material problems. After the audit phase we select the following initial needs: BoM creation, BoM management, BoM structuring for the production department, BoM integration in the ERP: The integration of the BoM in the ERP of the company is done manually, which is time consuming and source of error. The approach proposed here is based on the double view of the bill of material.

This case study enables us to identify the technical data that is transferred between the engineering department and the planning department in this company. It also allows us to extract the knowledge useful to their transfer and especially concerning the multi view of a product. We applied this multi-view notion using a buffer file that contains all the information of the product, the structuring of the product being specific to each view.

During this phase of immersion we integrated a knowledge management approach, based on the one exposed in the preceding sections of this paper, with first of all an extraction of fundamental knowledge, then a structuring of that knowledge and finally its integration into the software. The validation of this work was done by software tests carried out by the expert. Obviously the specific application integrated in the pilot companies are too specialized to be directly integrated into a generic model for the extended enterprise. Some of those data and some processes are really specific to the products manufactured by the company or to its production processes. Nevertheless some other can be processed in a general way and have been synthesized to create requirements related to the future generic PLM system.

5 Conclusions and perspectives

In this paper, we have presented a generic model for enterprise objects modeling that supports the encapsulation of knowledge [28]. This encapsulation is possible thanks to an extended generic method, based on an extended MOKA ontology (ICARREF) that aims to give a solution for the definition and the realization of knowledge-based applications.

An original inductive immersive approach lets us getting some very practical inputs and feedbacks on the application of these model and method that contribute to the improvement of the general approach we would like to propose to SMEs for the definition of their specific PLM needs.

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